

Marlo's windows: why it is a mistake to ignore hazard resistance in LCA

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Abstract

Purpose Hazard-resistant materials for homes promise environmental benefits, such as avoided waste and materials for repairs, which can be overlooked by scoping in life-cycle assessment (LCA) approaches. Our motivation for pursuing this research was to see how incorporating these avoided losses in the LCA could impact choices between hazard-resistant and traditional materials.

Methods Two choices common in home construction were analyzed using an LCA process that incorporates catastrophe modeling to consider avoided losses made possible with hazard-resistant materials. These findings were compared to those based on a similar LCA that did not consider these avoided losses. The choices considered were standard windows vs. windows with impact-resistant glass and standard windows with no opening protection vs. standard windows with impact-resistant storm panels.

Results and discussion For the window comparisons, the standard products were environmentally preferable when avoided losses from storm events were not considered in the LCA. However, when avoided losses were considered, the hazard-resistant products were environmentally preferable. Considering avoided losses in LCAs, as illustrated by the window choices, can change which product appears to be the environmentally preferable option. Further, as home service life increases, the environmental net benefit of the hazard-resistant product increases.

Conclusions Our results show the value of an LCA approach which allows more complete scopings of comparisons between hazard-resistant materials and their traditional counterparts. This approach will help translate the impacts of hazard-resistant products into the more familiar language used to talk about “green” products, enabling more informed decisions by product manufacturers, those who develop building certification systems and codes, researchers, and other building industry stakeholders.

Keywords Buildings · Catastrophe models · Durability · Hazard resistance · Hurricanes · Hybrid LCA · LCA · Resilience · Risk management · Windows

1 Introduction

Marlo James is a window supplier who does most of his business with homebuilders working in coastal Florida, near Miami. Marlo tries to do “the right thing” for his customers and for their environment. He works hard to maintain his deserved reputation for avoiding greenwashing and other misleading claims common in the building material industry (Terrachoice 2010). In fact, Marlo only sells materials for which he has performed a life-cycle assessment (LCA), and he provides his LCAs free of charge to prospective customers. Now, concerned about recent storms in the region and foreseeing more due to climate change and sea-level rise, Marlo's homebuilder customers are asking him whether they should make impact-resistant windows standard on the homes they build. What will Marlo's LCA say?

Marlo is made-up, but the scenario is real. Climate change combined with population growth in coastal regions has led to drastic increases in storm-related damages (Smith and Katz 2013). These trends are expected to continue (e.g., Grinsted

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et al. 2013), and in response, new markets have emerged for hazard-resistant products.

The scoping of LCA approaches often ignore the avoided losses and associated environmental benefits possible with hazard-resistant products (Padgett and Tapia 2012). This is an example of an exclusion problem in LCA scope definition, which can limit the accuracy and value of an LCA (Reap et al. 2008). When the benefits of avoided loss are overlooked, hazard-resistant systems may wrongly appear to be a less desirable environmental alternative. Consider Marlo's impact-resistant windows, which probably have additional aluminum framing reinforcements and glass treatments and therefore require more materials and energy to produce than standard windows. Marlo's regular LCA process could very well indicate that the standard windows are the preferable environmental option.

However, unlike regular windows, the impact-resistant windows are designed to crack but not fall apart, like a car windshield, keeping the home sealed even when the windows are struck by flying debris. Since the windows are still intact, there is a greatly reduced probability of water damage to interior furnishings or finishes. The sealed window opening also decreases the probability of other system failures, which tend to have a chain-like effect. Openings caused by broken windows, for example, lead to increased roof uplift pressures and failure, which in turn increases failure occurrence for walls (Committee on Structural Wind Engineering 2012). All of these damages require home repairs or replacements. Despite what his LCA says, Marlo wonders whether this negative environmental impact could outweigh the impact of the additional materials in his window choice.

Marlo's impact-resistant windows are just one example. Other hazard mitigating products include impact-rated doors, foundation anchoring, hurricane straps to better connect framing members, clay roof tiles, and storm shutters and impact-resistant storm panels for windows. Similar to Marlo's impact-resistant windows, each of these alternatives has additional materials, meaning the LCA could produce a poor recommendation.

1.1 Catastrophe modeling is the LCA of hazard assessment

LCA can improve decision-making for building construction and operation, to which we humans devote significant energy and material resources (UNEP 2003). Comparison LCAs of building materials are widespread, applicable to products such as windows (Citherlet et al. 2000; Recio et al. 2005; Salazar and Sowlati 2008), to assemblies such as building frames (Guggemos and Horvath 2005; Jonsson et al. 1998), and to entire buildings (Aktas and Bilec 2012; Ochoa 2004). However, an LCA approach which includes hazard resistance in the scope is needed to solve dilemmas like Marlo's. Literature and practice reveal no methods for fully considering the

environmental impacts of using hazard-resistant systems. The window LCAs referenced above, for example, do not account for the whole home benefits of hazard resistance.

Catastrophe modeling is to hazard impacts as what LCA is to environmental impacts. Catastrophe models have four basic parts: a hazard, inventory, vulnerability, and loss (Grossi and Kunreuther 2005). *Hazard* characterizes a specific event. Hurricane hazard, for example, is typically described using parameters such as location (projected path), severity (peak gust wind speed), and occurrence frequency. *Inventory* describes the properties at risk to the hazard. Inventory parameters include location, building type, number of stories, age, and hazard mitigation methods used. An inventory may be just one property, or millions, limited only by data availability and computational capabilities. As shown in Fig. 1, the hazard and inventory are combined to determine the *vulnerability* part of catastrophe modeling, which accounts for the susceptibility of the inventory to damage. This is done using damage functions, often graphed as curves relating hazard intensity to the percentage of the building damaged. For example, higher hurricane wind speeds are more likely to yield a greater percentage of home damage. Finally, the *loss* part of the catastrophe model calculates the economic loss to the inventory using the hazard and vulnerability parameters. A specific location has an annual rate of occurrence (p_i) for an event (E_i), which is defined as a catastrophe which could cause damage to the inventory. The expected loss for a given event in a given year is $E(L) = p_i L_i$. The average annual loss for an inventory is equal to the sum of every expected loss for a given year or $AAL = \sum p_i L_i$. The average annual loss is commonly used to set insurance premiums (Grossi and Kunreuther 2005).

An LCA that includes catastrophe modeling would more accurately account for the avoided losses possible with the impact-resistant windows. For Marlo's LCA, would this change the recommendation for the window choice that is environmentally preferable?

2 Methods

Using an LCA process which incorporates catastrophe modeling to consider avoided losses possible with hazard-resistant materials, we analyzed Marlo's choice between standard and impact-resistant windows. We also examined another choice common in home construction. We compared standard windows with no opening protection to standard windows with



Fig. 1 Catastrophe modeling combines hazard and inventory to estimate vulnerability and then loss

impact-resistant storm panels. This comparison was selected to illustrate a “do nothing” scenario where the production of storm panels has an environmental impact, whereas the alternative choice has no net environmental impact. For each of the choices, these findings were compared to findings from similar analysis that did not consider avoided losses.

2.1 The hazard LCA approach to account for environmental impacts of damages from hazards

Our hazard LCA (H-LCA) approach considers environmental impacts of hazard-related damages by incorporating catastrophe models. The initial steps for the H-LCA are familiar: define the goal and scope, including functional unit, system boundaries, and assumptions, as outlined in ISO 14040/14044 (ISO 2006). Unique to the H-LCA, catastrophe modeling data is used to determine average annual economic losses, which are then converted to environmental metrics using the Economic Input–output LCA tool (Green Design Institute 2012).

2.2 Goal, scope, functional unit, system boundaries, and assumptions

Descriptions in this section are for Marlo’s window choice. The same process was used for the other choice we analyzed (standard windows with no opening protection vs. standard windows with impact-resistant storm panels).

Goal: The goal of this LCA is to compare the environmental impacts of a home with impact-rated double-paned energy-efficient windows to the environmental impacts of a home with traditional double-paned energy-efficient windows in Miami, Florida, a region vulnerable to high wind events.

Scope: Hazard-induced damages related to window failure are not limited to the window system itself. So even though it is the window systems being compared, we defined the entire home as the functional unit to more accurately predict the effects of hazard resistance. The LCA includes manufacturing and construction, usage (including operations, repair, and maintenance), and disposal (end of life) phases.

Functional unit: The home includes 1,890 heated square feet and a 444-ft² garage. It is located in Miami, Florida, in the USA. The occupancy is three people, and the service life is 50 years. The only variable that differed between the two model homes was the hazard-resistant material choice under investigation.

System boundaries: Home assemblies included in the LCA are those which could be impacted by a failure of one of the material choices being analyzed: walls, floors, roofs, ceilings, foundation, basement, doors, windows, appliances, electrical system and fixtures, plumbing and

fixtures, cabinetry, finishes, porches, and decks. Omitted from the analysis are elements outside of the home including site work, infrastructure and municipal services, and utility hookups.

Assumptions about the material choices are as follows:

- There are 16 window openings, each 3 ft and 0 in. × 5 ft and 2 in. in size. Windows are operable, double-hung, with a PVC clad wood frame, and standard frame profile for the North American market. They are double glazed, with silver argon-filled low-emissivity glass and a 0.81 U-factor, which is a standard measure of heat loss for windows. Assumptions for maintenance were 3 % glazing replacement per year, sealant replacement every 8 years, and total removal and replacement of the window system every 16 years (these assumptions are from Athena LCA software defaults unless otherwise noted). The impact-resistant windows require additional glazing materials and processing as well as aluminum reinforcing clips to reduce vibrations.
- The impact-resistant storm panels are corrugated aluminum and weigh 6.5 lb per window opening. Their service life is longer than that of the house, as these panels are only used during storm events and therefore infrequently exposed to the elements.

2.3 Performing the LCA to include catastrophe modeling data

The Athena Impact Estimator for Buildings was used for the process-based LCA (Athena Sustainable Materials Institute 2010). We input general information about the home, including service life (50 years) and location.¹ The Athena includes predefined assemblies for major structural components of the home, including flooring, roofing, foundations, and walls. We represented the home as completely as possible with these assemblies and then added specific materials from Athena’s databases to account for components of the home not included in the assemblies. We modeled materials not included in Athena’s database using the default “Residential Building Construction” sector values in the Economic Input–output (EIO) LCA.

Energy consumption for the homes was estimated using Home Energy Saver Pro (U.S. DOE 2012). This online tool is organized into six major categories, each containing multiple prompts. When data specific to the case home was unavailable, default values were used, which take into account

¹ Atlanta, Georgia, was the closest location alternative to Miami. As this location is consistent for both model homes, location differences will have a negligible impact on final results. Because energy usage was calculated separately, climate differences between Atlanta and Miami do not affect operating energy results.

Table 1 Global warming potential—home with standard windows vs. home with impact-resistant windows (kg CO₂ eq, 50-year service life, 0 % environmental discount rate)

	Standard	Impact resistant	Difference	“Better” option
LCA (no hazard modeling)	757,646	759,662	+2,016	Standard
Disaster-related impacts	18,120	14,120		
H-LCA result	775,766	773,782	−1,984	Impact resistant

national and regional averages. The output from this program, annual energy usage of the home, was used as an input for the General Information section of the Athena Impact Estimator for Buildings.

Catastrophe modeling was incorporated using RiskLink software developed by Risk Management Solutions, an international catastrophic risk modeler. The home was modeled using general information including insured value, square footage, date constructed, and location. Other parameters, referred to as secondary modifiers, allowed us to analyze the impacts of our material choices on the expected losses. For the window-related decisions, the secondary modifier was “Opening Protection.” We created identical models for the home, changing only this secondary modifier of interest (the total number of windows and overall window square footage remained constant, and only the material properties were modified). Stochastic models were then run to compare the homes’ hazard-related economic losses. Direct losses include the removal and replacement of the hazard-resistant product or its conventional counterpart. Indirect losses include increased vulnerabilities or secondary damages that occurred due to product failures.

Because the only variable changed between the stochastic models was the window type, we were able to determine the difference in losses between the two choices. A home with Marlo’s impact-resistant windows, for example, might expect an annual loss of x in high wind event-related damages, whereas a similar home with the standard windows might expect an annual loss of y . In this example, subtracting x from y would give the annual differences in expected damages. Because the window properties were the only variable changed between the two catastrophe models, the annual differences represent the economic savings by using the impact-resistant windows. A similar approach could be applied for any hazard-resistant system which is modifiable in the stochastic models. These economic values were input into the EIO-LCA as “Residential Building Construction” values (sector number 23611) and then converted, using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) output (Bare 2002), to the following environmental impacts: *fossil fuel consumption, global warming potential, acidification potential, human health criteria, eutrophication, and smog potential*.

3 Results and discussion

When avoided losses *were not* considered in the LCA, Marlo’s impact-resistant windows appeared to be less environmentally preferable. Conversely, the LCA-recommended choice changed when these losses *were* considered. As shown in Table 1, the impact-resistant windows do have slightly higher global warming potential² before the disaster-related damages are considered. However, considering these damages, the home with standard windows has higher global warming potential. The window-related difference in global warming potential is very small in comparison with that of the entire home,³ but the amount is enough to change Marlo’s choice regarding which option appears to be environmentally preferable.

Including the avoided losses also changed the choice between impact-resistant storm panels and the do-nothing scenario in which the home does not use these panels. The materials and energy to produce the storm panels are reflected in the slightly higher amount of global warming potential shown in the first row of Table 2. So, when hazard-related impacts are ignored, the do-nothing scenario seems better, appearing to contribute less to global warming potential. With hazard-related impacts, however, the do-nothing scenario has a global warming potential that is higher than the scenario in which storm panels are installed. Just as occupancy-phase impacts should be included in an LCA of building insulation, maintenance and other indirect impacts should be included in an LCA of hazard-resistant materials. Failure to do so is an example of incomplete LCA scoping and can produce misleading results.

3.1 Sensitivity and uncertainty

As in any LCA comparison, uncertainty and sensitivity to other assumptions should be considered when modeling

² Global warming potential is shown since it is closely correlated with the other environmental indicators, unless the disaster-resistant product has an inordinately high contribution to any of the other key indicators, which was not the case here.

³ Roughly 2/3 of the overall global warming potential results from operational energy during the use of the home. Roughly 1/3 of the global warming potential results from embodied energy of the materials for the home. Of the embodied energy, roughly 3 % is from the windows themselves. The choices Marlo is making impact the embodied energy, but not the operational energy. Other hazard-resistant systems, for example, windows that included more insulation and impact resistance, may impact operational energy.

Table 2 Global warming potential—home with standard windows vs. home with windows and storm panels (kg CO₂ eq, 50-year service life, 0 % environmental discount rate)

	Standard	With storm panels	Difference	“Better” option
LCA (no hazard modeling)	757,646	757,880	+234	Standard
Disaster-related impacts	18,120	14,120		
H-LCA result	775,766	772,000	−3,766	With storm panels

hazard resistance. The uncertainty in results from any LCA is determined by the uncertainty in the data that it is based upon. In the building industry, proprietary production methods and variations in housing designs and building material production sites are among the factors which contribute to a lack of broadly applicable and accurate cradle to grave environmental data. The hazard modeling also introduces uncertainty. While these are robust models, they also rely on probabilities to forecast weather and climate events. The impact of these uncertainty limitations can be minimized in comparison LCAs by applying consistent assumptions to both options being compared. However, the uncertainty limitations should be considered when making conclusions based on the values in LCA results. In other words, Marlo can be more confident in the absolute comparison between window types than he can be about the exact value of the global warming potential values.

In addition to uncertainty, sensitivity to assumptions is also a consideration for any LCA. For example, results from a sensitivity analysis of the environmental discount rates applied to the window comparison are shown in Table 3. When the discount rate is 1 %, the hazard-resistant windows are the preferred option in terms of global warming potential. When the discount rate is 5 %, the regular windows are preferred. The negative environmental impacts of the hazard-resistant windows are additional materials, which occur in manufacturing and installation phases of the LCA. The main benefits of the hazard-resistant windows are in the reduced maintenance needs, which occur as future values. Consequently, for higher discount rates, the relative value of these maintenance benefits was lower. For hazard-resistant products similar to the impact-resistant windows, with negative environmental impacts in the manufacturing and installation phases and positive impacts in the use phase, selecting appropriate discount rates will be important.

We also tested sensitivity to assumptions about the service life of the home. The results in Tables 1 and 2 assume a 50-year service life. As shown in the bottom rows of Table 3, as

the service life of the home increases from 30 to 70 years, the global warming potential of both the home with standard windows and the home with impact-resistant windows increase similarly, and therefore, the service life does not affect the comparative results of the two components.

4 Conclusions

Our results show the need for more complete scopings of LCA comparisons between hazard-resistant materials and their traditional counterparts. Our results also give people like Marlo a way to analyze hazard-resistant products and communicate their benefits to those seeking to minimize environmental impacts. Though Marlo’s location in Miami means that he is concerned with high wind events such as hurricanes, the process described in this article is applicable to other hazards that can be modeled probabilistically. For instance, the environmental impacts of upgrading anchor bolts to prevent earthquake damages could be studied using the same approach. Similarly, while Marlo is concerned with windows, the same approach could also be used for larger assemblies (e.g., timber-framed veneer vs. brick cladding) and in commercial and industrial scenarios. The Athena Impact Estimator for Buildings can model a variety of building types, and EIO-LCA can be applied as long as there is cost information.

More accurate LCA data for the building industry as well as advances in hazard modeling will help reduce the previously mentioned uncertainty limitations. Advances are also needed to improve data for component replacement cycles, which currently do not consider premature replacements due to disaster damage (replacement cycles we used in our analyses do not explicitly take service-life-shortening disaster impacts into account). These advances would improve the usefulness of the H-LCA process, especially for LCAs that are not comparisons.

Future research could also develop geographic breakeven lines to indicate where the use of a hazard-resistant product

Table 3 Sensitivity analysis for discount rates and for service life—home with standard windows vs. home with impact-resistant windows (kg CO₂ eq)

	Standard	Impact resistant	Difference	“Better” option
1 % discount rate	624,789	623,523	−1,266	Impact resistant
5 % discount rate	325,771	325,897	+126	Standard
30-year service life	488,705	487,648	−1,057	Impact resistant
70-year service life	1,053,619	1,050,825	−2,794	Impact resistant

changes from an environmental benefit to an environmental cost. Because expected losses due to hazard are geographically dependent, each new location would currently require a unique analysis. For products meant to reduce damage from high wind events, breakeven lines would likely mimic wind hazard maps, where risk typically decreases as one moves inward from the coast. In high-risk areas, certain hazard-resistant products will be environmentally preferable to standard products. As the risk decreases, the hazard-related benefits of these products decrease and at some point will roughly equal zero. This would be the breakeven line. Geographic breakeven lines would quickly show people like Marlo, as well as those developing certification programs and building codes, where hazard-resistant products are the environmentally preferable option.

There are also implications for approaches like these beyond individual choices like Marlo's. Insurance requirements and building codes could mandate hazard-resistant systems in cases where they are preferable based on life cycle costing projections that include annual losses. Voluntary green building certification programs are beginning to adopt LCA-based product certification criteria. As with other advances, such as designing for better energy performance, building codes are following the lead of these voluntary programs (Trusty 2011). To account for potential environmental benefits gained by using hazard-resistant products, green building certifications and codes could incorporate the H-LCA process as part of the product certification framework. This article shows that incorporating hazard resistance can make the difference in which a product is selected.

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